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BROOKHAVEN
NATIONAL LABORATORY

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for the U.S. Department of Energy

Memo

Date: ***December 6, 2004***

To: ***Melvin VanEssendelft***

From: ***Benny Hooda***

Subject: ***NESHAPs Review of Tritium Production in Helium at the AGS Snake Magnet***

As per your request, a NESHAPs compliance review of the white paper titled "An Estimation of Tritium Production in Helium in the AGS Snake Magnet" by E. Lessard and A. Sidi-Yekhlef, dated November 22, 2004 was completed.

The AGS facility is compliant with NESHAPs regulations even though the potential for fugitive losses of tritium exits near the Snake Magnet cryogenic cooling system within the AGS Ring. The potential for tritium production in the liquid helium, used to cool the AGS Snake Magnet, is possible due to secondary and tertiary hadrons scattering and absorption interactions. Only a small quantity (19.5 mCi) of tritium in all three Snake Magnet cooling systems would be produced even with the most conservative assumptions; such as using the highest value of helium cross section, independent spallation cross section above 100 MeV energy and similar cross section for all types of particles/ interactions. The tritium saturation concentration in the AGS Ring will be well below the derived air concentration and consequently the fugitive losses, if any, to the environment will be insignificant.

Based on the conservative criteria that all the tritium produced in the magnet quench was released to the environment, a NESHAPs compliance dose estimate was done using the EPA's CAP88-PC, version 3.0 dose modeling program. The potential effective dose equivalent was well below the 10 mrem/year annual limit as specified in the 40 CFR 61, subpart H, and below the 0.1mrem/ yr. limit, which would require a NESHAPs permit, and continuous monitoring of the emission source. The synopsis report from the dose-modeling program is attached that gives the effective dose equivalent to the maximally exposed individual in the southwest direction as 3.39E-8 mrem/year. An annual confirmatory air sample taken and analyzed for gamma emitting radionuclides in accordance with C-A OPM 9.5.12 also showed that there were no emissions of any other radionuclide from the AGS Ring.

If you have any questions regarding the NESHAPs review, please call Benny Hooda at extension 8107.

BH:car

Distribution: G. Goode, R. Karol, R. Lee, E. Lessard, A. Sidi-Yekhlef, R. Travis

File: EC72ER.04

* * *

C A P 8 8 - P C

Version 3.0

Clean Air Act Assessment Package - 1988

S Y N O P S I S   R E P O R T

Non-Radon Population Assessment
Dec 3, 2004 01:02 pmm

Facility: AGS Ring (Building 913)
Address: Brookhaven National Laboratory
P.O. Box 5000
City: Upton
State: NY   Zip: 11973

Source Category: Area
Source Type: Area
Emission Year: 2005

Comments: Tritium Production due to Hadrons interaction
with liquid helium cooling snake magnets at the AG

Effective Dose Equivalent
(mrem/year)

3.39E-08

At This Location: 1600 Meters Southwest

Dataset Name: AGS_2005
Dataset Date: 12/3/2004 1:02:00 PM
Wind File: Z:\CAP88PC2\CAP88PC2\WNDFILES\BNL00.WND
Population File: C:\Program Files\CAP88-PC30\Poplib\BNLB01.PO

MAXIMALLY EXPOSED INDIVIDUAL

Location Of The Individual: 1600 Meters Southwest
Lifetime Fatal Cancer Risk: 1.06E-12

FREQUENCY DISTRIBUTION OF LIFETIME FATAL CANCER RISKS

Risk Range	# of People	# of People in This Risk Range or Higher	Deaths/Year in This Risk Range	Deaths/Year in This Risk Range or Higher
1.0E+00 TO 1.0E-01	0	0	0.00E+00	0.00E+00
1.0E-01 TO 1.0E-02	0	0	0.00E+00	0.00E+00
1.0E-02 TO 1.0E-03	0	0	0.00E+00	0.00E+00
1.0E-03 TO 1.0E-04	0	0	0.00E+00	0.00E+00
1.0E-04 TO 1.0E-05	0	0	0.00E+00	0.00E+00
1.0E-05 TO 1.0E-06	0	0	0.00E+00	0.00E+00
LESS THAN 1.0E-06	5047193	5047193	1.05E-09	1.05E-09

RADIONUCLIDE EMISSIONS DURING THE YEAR 2005

			Source #1	TOTAL
Nuclide	Class	Size	Ci/y	Ci/y
H-3	V	0.00	2.0E-02	2.0E-02

SITE INFORMATION

Temperature: 10 degrees C
Precipitation: 110 cm/y
Humidity: 8 g/cu m
Mixing Height: 1000 m

SOURCE INFORMATION

Source Number: 1

Source Height (m): 2.00
Area (sq m): 4.00

Plume Rise Pasquill Cat:	A	B	C	D	E	F	G
Zero:	0.00	0.00	0.00	0.00	0.00	0.00	0.00

AGRICULTURAL DATA

	Vegetable	Milk	Meat
Fraction Home Produced:	0.000	0.000	0.000
Fraction From Assessment Area:	0.000	0.000	0.000
Fraction Imported:	1.000	1.000	1.000

Beef Cattle Density: 5.83E-02
Milk Cattle Density: 8.56E-02
Land Fraction Cultivated
for Vegetable Crops: 1.88E-02

POPULATION DATA

Distance (m)

Direction	250	850	1600	2250	2750	6300	16800
N	0	0	0	0	1	4650	0
NNW	0	0	0	1	1	7845	0
NW	0	0	0	0	1	18410	1605
WNW	0	0	0	0	1	42735	59885
W	0	0	0	0	1	50715	137075
WSW	0	0	0	0	1	38830	147520
SW	0	0	97	0	1	22325	66440
SSW	0	0	198	0	1	21875	1120
S	0	0	0	0	1	15900	35
SSE	0	0	0	0	1	22925	0
SE	0	0	0	1	1	9270	16325
ESE	0	0	0	0	1	6375	7080
E	0	0	0	0	1	3095	765
ENE	0	0	0	0	1	2540	0
NE	0	0	0	0	1	3015	0
NNE	0	0	0	0	1	7740	0

Distance (m)

Direction	32000	48000	64000
N	94925	252075	262180
NNW	211745	108585	54880
NW	137435	124535	104675
WNW	135	217780	131090
W	243225	227190	373120
WSW	360480	427075	778140
SW	3495	0	0
SSW	0	0	0
S	0	0	0
SSE	0	0	0
SE	0	0	0
ESE	0	0	0
E	11765	9250	585
ENE	13175	15220	2300
NE	0	13750	33525
NNE	7125	45010	66315

An Estimation of Tritium Production in Helium in the AGS Snake Magnet

Edward T. Lessard and Ahmed Sidi-Yekhlef

November 22, 2004

The AGS beam for part of the FY2005 running period for the nuclear physics program will be high-energy polarized protons directed from the AGS to the AtR transfer line. Some protons will be displaced from the beam within the ASG Ring. Secondary and tertiary hadrons arising from primary beam losses will interact in the helium liquid that cools the AGS Snake Magnet, which is used to maintain the polarization of protons in the beam. The question was raised as to whether AGS beam losses in the vicinity of the Snake Magnet would generate a significant amount of tritium in the liquid helium coolant and if there would be significant tritium gas emission in the helium boil off that would be routinely vented from the AGS Ring. This note presents calculations to address those questions.

The basic assumption is that heat in the Snake Magnet cryogenic cooling system is from ionization in the coolant. This is an overestimate of the amount of ionization in the coolant but it is done this way in order to quantify the maximum possible release of tritium while simplifying the determination of the irradiating fluence. It is noted that operation of the Snake Magnet cooling system outside its anticipated parameter for heat load, 2 watts, is not intended for significant periods of time. There are three cryo-coolers each capable of removing about 1.5 watts for helium at 4.5 ^{o}K. It is not possible to run the Snake Magnet if the heat load exceeds the total capacity of the cryo-coolers.

Beginning with a well-established formula for activation:[1]

$$P = \sum_{jk} N \int_{E_{jk}}^{E_{kmax}} \sigma_{jk}(E)\ \varphi_k \, dE \qquad \text{Eq. 1}$$

where P is the constant production rate of tritium atoms in the helium, atoms s^{-1},
N is the number of He atoms in the cooling system,
σ_{jk} is the cross section for a particle of type k producing a tritium atom via reaction j, cm^2,
φ_k is the fluence rate of particles of type k, particles/cm^2 s,
E is the particle energy, with E_{jk} being the threshold energy for reaction j with particle k, and $E_{k\max}$ is the maximum energy of particle type k.

This first equation assumes that there is only one radionuclide of interest, tritium. Some other simplifying assumptions are:

- The production of tritium is dominated by hadronic-spallation reactions, without significant contributions from reactions involving leptons, photons or secondary processes. This assumption eliminates the summation over *j*.
- The cross section for tritium production is essentially the same for all hadrons. This is reasonable given spallation is a strong interaction and eliminates the summation over *k*, allowing one to use the total number of hadrons to calculate φ.
- The spallation cross section is essentially independent of hadron energy above 100 MeV.[1] This assumption eliminates the integration over *E*.

Using first-order linear kinetics, the number tritium atoms in the coolant at any time is given by:[2]

$$H = \frac{P(1 - e^{-(\lambda + K)t})}{\lambda + K} \quad \text{Eq. 2}$$

where H is the number of tritium atoms in the helium coolant at any time,
λ is the decay constant of tritium = 1.79×10^{-9} s^{-1},
K is the boil-off constant for tritium, 0.1 g s^{-1}/12300 g = 8.13x10^{-6} s^{-1}, and
t is the irradiation time.

This second equation allows for no decay post shutdown; that is, it gives the tritium atoms at the moment the beam is turned off. The second equation also assumes there are two tritium removal rates at work during irradiation: loss of tritium due to helium boil-off and due to radioactive decay.

Combining the first and second equations with the simplifying assumptions yields:

$$H = \frac{N\sigma\varphi(1 - e^{-(\lambda + K)t})}{\lambda + K} \quad \text{Eq. 3}$$

Determination of N is straightforward from Avogadro's number, the mass of liquid helium in the Snake Magnet and the molecular weight of liquid helium:

$$N = \frac{\rho}{M} N_A = \text{(12300 g / 4.00 g mol}^{-1}\text{)(6.02x10}^{23}\text{ atoms mol}^{-1}\text{) = 1.85x10}^{27}\text{ atoms}$$

Deciding on a value for cross section for tritium production from spallation of helium by hadrons is less straightforward and represents most of the uncertainty in this estimate. No measured cross section for the production of tritium through hadronic spallation of helium has been located. However, tritium production cross sections have been compiled for reactions with other targets.[3] Plots of cross section versus atomic number show the cross section falling for light elements. Visual inspection places the cross section for helium-4 as low as 5 mb or as high as 30 mb. Additionally, one can calculate 30 mb for the cross section using Reference 4. Thus, 30 mb is chosen here as a reasonable yet conservative estimate for cross section for this specific reaction on helium.

The following assumptions are made in estimating fluence rate, φ. The heat load in the liquid helium is reported to be 2 watts under normal operation. This heat load is assumed to be due to secondary and tertiary hadron interactions in helium. The absorbed dose per unit hadron fluence is taken from Reference 5, page 24, as $3.2\text{x}10^{-14}$ Gy m^2 hadron^{-1}. The fluence rate into the helium coolant can be calculated from the heat load and absorbed dose per unit hadron fluence as follows:

$$\varphi = (2 \text{ watts}/12300 \text{ g})(10^7 \text{ erg/s/watt})(1 \text{ rad}/100 \text{ ergs g}^{-1})(1 \text{ Gy}/100 \text{ rad})/(3.2\text{x}10^{-14} \text{ Gy m}^2 \text{ hadron}^{-1})$$

$$\varphi = 5.08\text{x}10^{12} \text{ hadrons/m}^2 \text{ s}$$

The irradiation time is assumed to be eight weeks, which is $4.84\text{x}10^6$ s. Using Eq. 3, the number of tritium atoms in the helium coolant at the end of eight weeks is:

$$H = (1.85\text{x}10^{27} \text{ atoms})(30 \text{ mb})(10^{-27} \text{ cm}^2/\text{mb})(5.08\text{x}10^{12} \text{ hadrons/m}^2 \text{ s})(1 \text{ m}^2/10^4 \text{ cm}^2)(1\text{-e}^{-(0.00000000179/\text{s} + 0.00000813/\text{s})(4{,}840{,}000 \text{ s})})/(1.79 \times 10^{-9} \text{ s}^{-1} + 8.13\text{x}10^{-6} \text{ s}^{-1})$$

$$H = 3.47\text{x}10^{15} \text{ tritium atoms}$$

The tritium activity, A, in the helium coolant is given by:

$$A = H\,\lambda$$

$$A = (3.47\text{x}10^{15} \text{ tritium atoms})(1.79\text{x}10^{-9} \text{ s}^{-1})$$

$$A = 1.68\text{x}10^{8} \text{ pCi}$$

$$A = 6.22\text{x}10^{6} \text{ Bq}$$

The tritium release rate, Q, from boil-off is given by:

$$Q = HK$$

$$Q = (3.47\text{x}10^{15} \text{ tritium atoms})(8.13\text{x}10^{-6} \text{ s}^{-1})$$

$$Q = 2.82\text{x}10^{10} \text{ atoms/s}$$

$$Q = 1360 \text{ pCi/s}$$

$$Q = 50.3 \text{ Bq/s}$$

The Derived Air Concentration (DAC) for the Annual Limit on Intake of a radionuclide is that concentration which will deliver the annual limit of dose equivalent to a worker who continuously occupies an area at one DAC for one working year (2000 hours). In the case of tritium, the DAC is $8x10^5$ Bq/ml.[6] The tritium in the Snake Magnet is mixed with 12300 g of liquid helium, which is $9.8x10^4$ cc of liquid, and the liquid to gas expansion ratio is 768 at 300 ^oK. The resulting airborne tritium concentration is at least seven orders of magnitude less than the DAC, and it would exist temporarily in the vicinity of the Snake Magnet after a loss of coolant event inside the AGS Ring. Therefore, no significant radiological hazard to a worker exists.

From the standpoint of environmental protection, one considers the total amount of tritium released from a magnet quench and assumes that all of it is vented to the outside. The other environmental consideration is routine emission of tritium with the helium boil off for eight weeks of operation. Using EPA's CAP88 Code with BNL site parameters, the maximum dose to an individual off site would be $1.8x10^{-8}$ mrem for the quench event and $6.8x10^{-7}$ mrem during the eight week program from routine tritium emissions.[7] Even if the cryo-coolers were run at full capacity of 4.5 watts, rather than at the expected routine level of 2 watts, off-site doses would be well below the 0.1 mrem per year trigger for monitoring requirements prescribed by EPA in 40 CFR 61.

References

1. H. W. Patterson and R. H. Thomas, Accelerator Health Physics, p. 519, Academic Press, New York (1973)
2. Skrable K., French C., Chabot G., Major A., A General Equation For The Kinetics Of Linear First Order Phenomena And Suggested Applications, Health Phys. 27(1):155-7, (1974).
3. A. Konobeyev and A. Korovin, Nuclear Instruments And Methods, V 82, p.103, (1993)
4. M. Barbier, Induced Radioactivity, North-Holland Publishing Company, Amsterdam and London (1969)
5. A. H. Sullivan, A Guide to Radiation and Radioactivity Levels Near High Energy Particle Accelerators, Nuclear Technology Publishing, Kent, England (1992)
6. U. S. Department of Energy, *Occupational Radiation Protection; Final Rule*, 10 CFR 835, Appendix A, (1993)
7. U. S. Environmental Protection Agency, CAP88-PC provides a framework for developing inputs to perform dose and risk assessments in a Windows environment for the purpose of demonstrating compliance with 40 CFR 61.93(a). For questions about this program, please contact:
Sanjib Chaki, P.E.
Environmental Engineer
U. S. Environmental Protection Agency
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BROOKHAVEN
NATIONAL LABORATORY

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Memo

Date: *April 4, 2005*

To: *Melvin VanEssendelft*

From: *Benny Hooda*

Subject: *NESHAPs Evaluation of Radionuclide Production in the Nitrogen at the AGS Snake Magnet*

As per your request, NESHAPs compliance review of the white paper titled "An Estimation of Radionuclide Production in Nitrogen in the AGS Snake Magnet" by E. Lessard, dated March 29, 2005 was completed.

The AGS Snake Magnet is pre-cooled with liquid nitrogen for up to about 10 days and then switched over to the helium cooling system. The potential for tritium production in the liquid helium was evaluated earlier, and the AGS facility was found to be compliant with NESHAPs regulation for fugitive losses of the tritium. In this evaluation, the radionuclides produced in liquid nitrogen were evaluated for NESHAPs compliance. The scatter and absorption interactions of the protons losses from the high-energy polarized beam can produce secondary and tertiary hadrons, which potentially could interact with the liquid nitrogen used to pre-cool the AGS Snake Magnet. Only trace amounts of H-3 and Be-7 will be produced in the liquid nitrogen considered in this risk assessment. Production of C-11 and N-13 radionuclides in the liquid nitrogen at saturation concentration was also very low and due to their short half-lives, the fugitive losses to the environment will be insignificant.

A NESHAPs compliance dose assessment was completed using the EPA's CAP88-PC, version 2.10 dose modeling program. The potential effective dose equivalent was well below the 10 mrem/year annual limit as specified in the 40 CFR 61, subpart H, and below the 0.1mrem/ yr. limit, which would require a NESHAPs permit, and continuous monitoring of the source. The synopsis report from the dose-modeling program is attached which gives the effective dose equivalent to the maximally exposed individual in the northwest direction to be 9.88E-7 mrem/year. The radiological hazard from emissions was the external immersion dose in the immediate vicinity of the AGS Ring and there was no dose risk to the members of the public.

If you have any questions regarding the NESHAPs review, please call Benny Hooda at extension 8107.

BH: car

Distribution: G. Goode, R. Karol, R. Lee, E. Lessard, A. Sidi-Yekhlef, R. Travis

File: **EC72ER.05**

* * *

Version 2.10

Clean Air Act Assessment Package - 1988

SYNOPSIS REPORT

Non-Radon Population Assessment
Apr 1, 2005 01:54 pm

Facility: AGS (Building 931)
Address: Brookhaven National Laboratory
P.O.Box 5000
City: Upton
State: NY Zip: 11973

Source Category: Area
Source Type: Area
Emission Year: 2005

Comments: Radionuclide Production in Nitrogen
in the Snake magnet at the AGS

Effective Dose Equivalent
(mrem/year)

9.88E-07

At This Location: 1400 Meters Northwest

Dataset Name: AGS
Dataset Date: 4/1/2005 1:54:00 PM
Wind File: Z:\CAP88PC2\CAP88PC2\WNDFILES\BNL00.WND
Population File: Z:\CAP88PC2\CAP88PC2\POPFILES\BNL1.POP

RADIONUCLIDE EMISSIONS DURING THE YEAR 2005

			Source	
			#1	TOTAL
Nuclide	Class	Size	Ci/y	Ci/y
H-3	*	0.00	3.8E-08	3.8E-08
BE-7	Y	1.00	3.2E-06	3.2E-06
C-11	D	1.00	1.0E-02	1.0E-02
N-13	D	1.00	1.0E-02	1.0E-02

SITE INFORMATION

Temperature: 10 degrees C
Precipitation: 121 cm/y
Humidity: 8 g/cu m
Mixing Height: 1000 m

POPULATION DATA

	Distance (m)						
Direction	500	1400	2050	2550	3050	9650	24000
N	0	0	0	0	1	4650	0
NNW	0	0	0	0	1	7845	0
NW	0	1	0	0	1	18410	1605
WNW	0	0	0	0	1	42735	59885
W	0	0	0	0	1	50715	137075
WSW	0	0	97	0	1	38830	147520
SW	0	0	198	0	1	22325	66440
SSW	0	0	0	0	1	21875	1120
S	0	0	0	0	1	15900	35
SSE	0	0	0	0	1	22925	0
SE	0	0	0	0	1	9270	16325
ESE	0	0	0	0	1	6375	7080
E	0	0	0	0	1	3095	765
ENE	0	0	0	0	1	2540	0
NE	0	0	0	0	1	3015	0
NNE	0	0	0	0	1	7740	0

	Distance (m)		
Direction	40000	56000	72000
N	94925	252075	262180
NNW	211745	108585	54880
NW	137435	124535	104675
WNW	135	217780	131090
W	243225	227190	373120
WSW	360480	427075	778140
SW	3495	0	0
SSW	0	0	0
S	0	0	0
SSE	0	0	0
SE	0	0	0
ESE	0	0	0
E	17765	9250	585
ENE	13175	15220	2300
NE	0	13750	33525
NNE	7125	45010	66315

An Estimation of Radionuclide Production in Nitrogen in the AGS Snake Magnet (Revision 2.0)

Edward T. Lessard

March 29, 2005

The AGS beam for part of the FY2005 running period for the nuclear physics program will be high-energy polarized protons directed from the AGS to the AtR transfer line. Some protons will be displaced from the beam within the ASG Ring. Secondary and tertiary hadrons arising from primary beam losses will interact in the nitrogen that is used to pre-cool the AGS Snake Magnet. Tritium production in the helium coolant has already been considered and reviewed for NESHAPs compliance.[1] The question was raised as to whether AGS beam losses in the vicinity of the Snake Magnet during pre-cooling would generate a significant amount of radioactivity and if there would be significant radioactive gas emission in the nitrogen flow that would be vented from the AGS Ring. This note presents calculations to address those questions.

The basic assumption is that the liquid nitrogen in the Snake Magnet's cold mass (10 L) receives 0.10 Gy per hour[2] for up to 10 days during the pre-cooling period, and then the Snake Magnet is switched over to helium cooling. The irradiation comes from concurrent operations in the AGS for setup of polarized proton beam. This dose to nitrogen is an overestimate, but it helps quantify the maximum possible release of radioactivity while simplifying the determination of the irradiating fluence. Based on Sullivan,[3] the secondary hadron fluence per unit absorbed dose is:

$$3.2\times10^{-14} \text{ Gy m}^2 \text{ hadron}^{-1}$$

Thus, the irradiating fluence rate is:

$$8.7\times10^{4} \text{ hadrons cm}^{-2} \text{ s}^{-1}$$

[1] NESHAPs Review of Tritium Production in Helium in the AGS Snake Magnet, B. Hooda to M. Van Essendelft, BNL Memorandum, December 6, 2004.
[2] Private communication with J. W Glenn and based on past experience.
[3] A. H. Sullivan, A Guide to Radiation and Radioactivity Levels Near High Energy Particle Accelerators, Nuclear Technology Publishing, Kent, England (1992)

Beginning with a well-established formula for activation:[4]

$$P = \sum_{jk} N \int_{E_{jk}}^{E_{kmax}} \sigma_{jk}(E)\ \varphi_k\, dE \qquad \text{Eq. 1}$$

where P is the constant production rate of a particular radioactive species in the liquid nitrogen, atoms s^{-1},
N is the number of liquid nitrogen atoms in the cold mass of the Snake Magnet,
σ_{jk} is the cross section for a particle of type k producing a particular radioactive species via reaction j, cm^2,
φ_k is the fluence rate of particles of type k, particles/cm^2 s,
E is the particle energy, with E_{jk} being the threshold energy for reaction j with particle k, and $E_{k\max}$ is the maximum energy of particle type k.

Each radionuclide of interest must be treated separately using Eq. 1. The radionuclides of interest are 10 minute ^{13}N, 20 minute ^{11}C, 53 day ^{7}Be and 12.3 year tritium. Some other simplifying assumptions are:

- The production of each type of radionuclide is dominated by hadronic-spallation reactions, without significant contributions from reactions involving leptons, photons or secondary processes. This assumption eliminates the summation over j.
- The cross section for production of a particular radionuclide of interest is essentially the same for all hadrons. This is reasonable given spallation is a strong interaction and eliminates the summation over k, allowing one to use the total number of hadrons to calculate φ.
- The spallation cross section is essentially independent of hadron energy above 100 MeV (Footnote 3). This assumption eliminates the integration over E.

Using first-order linear kinetics, the number radioactive atoms in the coolant at any time is given by:[5]

$$H = \frac{P(1 - e^{-(\lambda + K)t})}{\lambda + K} \qquad \text{Eq. 2}$$

where H is the number of radioactive atoms of a particular species in the nitrogen coolant at any time t,
λ is the decay constant of particular radionuclide of interest (tritium is $1.79 \times 10^{-9}\ s^{-1}$, ^{13}N is $9.63 \times 10^{-4}\ s^{-1}$, ^{11}C is $6.42 \times 10^{-4}\ s^{-1}$ and ^{7}Be is $1.50 \times 10^{-7}\ s^{-1}$)
K is the boil-off constant for nitrogen plus its radioactive contaminates; that is, liquid

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[4] H. W. Patterson and R. H. Thomas, Accelerator Health Physics, p. 519, Academic Press, New York (1973).

[5] Skrable K., French C., Chabot G., Major A., A General Equation For The Kinetics Of Linear First Order Phenomena And Suggested Applications, Health Phys. 27(1):155-7, (1974).

nitrogen flow rate divided by cold mass volume, (1200 L/[(24 h)(3600 s h^{-1})(10 L)] = $1.39\text{x}10^{-3}$ s^{-1}, and
t is the irradiation time.

This second equation allows for no decay post shutdown; that is, it gives the radioactive atoms of interest at the moment the AGS polarized proton beam is turned off. The second equation also assumes there are two removal rates at work during irradiation: loss of radioactive atoms due to liquid nitrogen flow out of the cold mass and loss due to radioactive decay.

Combining the first and second equations with the simplifying assumptions yields:

$$H = \frac{N\sigma\varphi(1-e^{-(\lambda+K)t})}{\lambda+K} \quad \text{Eq. 3}$$

Determination of N is straightforward from Avogadro's number, N_A, the mass of liquid nitrogen in the Snake Magnet, ρ, and the molecular weight of liquid nitrogen, M:

$$N = \frac{\rho}{M}N_A = (8080\text{ g} / 14\text{ g mol}^{-1})(6.02\text{x}10^{23}\text{ atoms mol}^{-1}) = 3.48\text{x}10^{26}\text{ atoms}$$

The value for cross section for production of all these low-mass radionuclides of interest from spallation of nitrogen by secondary high energy hadrons is 30 mb.[6] The ^{13}N, ^{11}C and ^{7}Be cross-sections have been reported to be in the 10 to 30 mb range and 30 mb was chosen in order to overestimate the amount of radioactivity present.

Because of the large liquid nitrogen flow rate and small cold mass volume, a steady state level of radioactive atoms is reached within a few tens of minutes in the liquid cold mass volume. This further simplifies Eq. 3 since $(1\text{-}e^{-(\lambda+K)})$ equals 1 in this case. Using Eq. 3, the radioactive atoms in the nitrogen coolant at steady state are:

$$H_{tritium} = (3.48\text{x}10^{26}\text{ atoms})(30\text{ mb})(10^{-27}\text{ cm}^2/\text{mb})(8.7\text{x}10^4\text{ hadrons/cm}^2\text{ s})/ (1.79\times10^{-9}\text{ s}^{-1} + 1.39\text{x}10^{-3}\text{ s}^{-1})$$

$$H_{tritium} = 6.53\text{x}10^8\text{ tritium atoms}$$

$$H_{C\text{-}11} = (3.48\text{x}10^{26}\text{ atoms})(30\text{ mb})(10^{-27}\text{ cm}^2/\text{mb})(8.7\text{x}10^4\text{ hadrons/cm}^2\text{ s})/ (6.42\text{x}10^{-4}\text{ s}^{-1} + 1.39\text{x}10^{-3}\text{ s}^{-1})$$

$$H_{C\text{-}11} = 4.53\text{x}10^8\ ^{11}\text{C atoms}$$

$$H_{N\text{-}13} = (3.48\text{x}10^{26}\text{ atoms})(30\text{ mb})(10^{-27}\text{ cm}^2/\text{mb})(8.7\text{x}10^4\text{ hadrons/cm}^2\text{ s})/ (9.63\text{x}10^{-4}\text{ s}^{-1} + 1.39\text{x}10^{-3}\text{ s}^{-1})$$

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[6] M. Barbier, Induced Radioactivity, North-Holland Publishing Company, Amsterdam and London (1969).

$H_{N-13} = 3.86x10^8$ ^{13}N atoms

$H_{Be-7} = (3.48x10^{26}$ atoms)(30 mb)(10^{-27} cm^2/mb)($8.7x10^4$ hadrons/cm^2 s)/
($1.50x10^{-7}$ s^{-1} + $1.39x10^{-3}$ s^{-1})

$H_{Be-7} = 6.53x10^8$ ^7Be atoms

The radionuclide activity, A, in the liquid nitrogen coolant is given by:

$A = H\lambda$

For example:

$A_{tritium}$ = ($6.53x10^8$ tritium atoms)($1.79x10^{-9}$ s^{-1})

$A_{tritium}$ = 1.17 Bq

The activity release rate, Q, from boil-off is given by:

$Q = AK$

For example:

$Q_{tritium}$ = (1.17Bq)($1.39x10^{-3}$ s^{-1})

$Q_{tritium}$ = $1.62x10^{-3}$ Bq s^{-1}

The steady state release rates from liquid nitrogen cold mass in the Snake Magnet for all radionuclides of interest are summarized in Table 1.

Table 1 Summary of Steady State Release Rates with Concurrent Polarized Proton Beam in the AGS during Liquid Nitrogen Pre-Cooling

Radionuclide of Interest	Steady State Activity in Cold Mass Volume, Bq	Steady State Activity Release Rate, Bq s^{-1}	Steady State Activity Release Rate, pCi s^{-1}
Tritium	1.17	0.0016	0.044
Be-7	97.9	0.14	3.7
C-11	294,000	410	11,000
N-13	372,000	520	14,000

The Derived Air Concentration (DAC) for the Annual Limit on Intake of a radionuclide is that concentration which will deliver the annual limit of dose equivalent to a worker who continuously occupies an area at one DAC for one working year (2000 hours).[7] The radioactivity in the Snake Magnet is mixed in 10 L (0.01 m^3) of liquid nitrogen, and the liquid nitrogen to gas expansion ratio is 700 at 300 ^oK. The resulting airborne concentrations in the 7 m^3 volume of room temperature nitrogen gas are many orders of magnitude less than the DAC for ^7Be and tritium, but about 50% of the DAC for ^{11}C and ^{13}N, see Table 2. The airborne activity would exist temporarily, a few minutes, in the vicinity of the Snake Magnet after a loss of coolant event inside the AGS Ring. The DAC for ^{11}C and ^{13}N is computed by assuming immersion in a cloud with resultant whole body exposure. ^{13}N would not be absorbed into body tissue, and ^{11}C would not be taken up in tissue to an extent that internal exposure would be significant relative to the external exposure. In this case, the dose equivalent rate for the brief period of time one might be immersed in the cloud of gas in the AGS tunnel would be about 1.5 mrem per hour, predominantly from external exposure and not intake.[8] Therefore, no significant radiological hazard to a worker exists since the cloud would dissipate within a few minutes. However, there would be dispersible contamination on the skin and clothes that would decay away quickly. Thus, entry into the AGS to investigate a large loss of liquid nitrogen should be delayed 30 minutes, or protective clothing should be worn.

Table 2 Maximum Airborne Radionuclide Concentration if Cold Mass Radioactivity Inventory is Released to AGS Tunnel

Radionuclide of Interest	Steady State Activity in Cold Mass Volume, Bq	Activity Concentration in AGS Tunnel, Bq m^3	Derived Air Concentration (DAC) Limit, Bq m^3
Tritium	1.17	0.17	800,000
Be-7	97.9	14	300,000
C-11	294,000	42,000	100,000[9]
N-13	372,000	53,000	100,000[9]

From the standpoint of environmental protection, one considers the total amount of radioactivity released via routine emission with the nitrogen flow for 10 days of operation. Using EPA's CAP88 Code with BNL site parameters, the maximum dose to an individual off site would be well below the 0.1 mrem per year trigger for monitoring requirements prescribed by EPA in 40 CFR 61.

[7] U. S. Department of Energy, *Occupational Radiation Protection; Final Rule*, 10 CFR 835, Subpart A, §835.2 (1-1-99).
[8] Immersion dose assumed; External Dose-Rate Conversion Factors for Calculation of Dose to the Public, US Department of Energy, DE88-014691, July 1988.
[9] U. S. Department of Energy, *Occupational Radiation Protection; Final Rule*, 10 CFR 835, Appendix C, (1-1-99).